SMALL-EVENT YIELD AND SOURCE CHARACTERIZATION USING LOCAL P AND S-WAVE CODA SOURCE SPECTRA

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ABSTRACT

The mission of the Air Force Technical Applications Center (AFTAC) requires accurate yield estimation for nuclear explosions. Historically, the focus has been on larger yield events (m_b > ~4.5) using teleseismic body wave magnitudes and applying test-site-specific corrections for yield estimates. The regional coda methodology provides unprecedented stability and avoids test site bias because it is based upon absolute source spectra. Increasingly, however, there is interest in monitoring smaller events both for yield and source characterization. Unfortunately, these events may only be recorded with adequate signal-to-noise ratio at local distances from one station.

The project goals were to extend the well-established regional coda methodology to local distances using *S* and *P*-wave codas in regions of little-to-no calibration data and/or regions of high attenuation and lateral complexity. Previous studies show that local coda has a unique property of homogenizing its energy over a volume of the Earth's crust such that path corrections for distances less than ~200 km are not necessary, or minimal at worst. Our plan this year was to use existing datasets from a variety of active tectonic settings and source types with the aim of assessing performance under the assumption of little to no calibration data. We have compared S-wave coda path attenuation curves from a variety of regions to look for similarities and differences that could be correlated to the degree of tectonic activity. In general, we can make some preliminary statements. First, we find that central Italy exhibits the strongest attenuation (0.5 to 2.0 Hz), followed by Taiwan and western Iran for distances ranging between ~20 and 300 km. On the other hand, upstate New York, South Africa, and the Korean Peninsula appear to have the lowest attenuation, which is reassuring since both regions are the most tectonically stable. The San Francisco Bay Area is somewhere between the two.

This special feature may make it easier to define an a priori set of coda-calibration parameters that can be transported to new but geophysically similar regions. For example, it appears that tectonically similar regions have similar a coda path, envelope shape, and peak envelope velocity, which will allow us to derive average "local background" models then apply them to other regions for testing and evaluation, including cases to mimic an uncalibrated, single-station deployment.

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OBJECTIVES

The following outlines many of the questions and objectives that are being addressed in this study:

1) To what extent can an average local background coda model (e.g., path corrections, envelope shape, velocity, etc.) be developed and transported to a new area with no prior calibration? Specifically, can we transport these averaged parameters to a new, tectonically similar region? What are the associated errors?
2) For regional coda calibrations that lack local data and are unconstrained at these distances (e.g., central Asia, North Africa), can we seamlessly blend in the appropriate local background model?
3) Can local coda measurements in a heterogeneous region provide a stable yield estimate relative to direct wave measures?
4) Due to its inherent shorter window length, to what extent can the local *P*-wave coda be used and how do results compare with *S* coda? How does this compare with results from an ongoing regional *P*-wave coda study?
5) How much is gained by additional stations, or is one station enough?
6) For low seismicity regions, how can we obtain higher confidence estimates of site-response corrections? For example, can we use a single ground-truth source spectrum or calibration event? If so, what are the errors?
7) For highly attenuative regions, what is the minimum coda window length needed to maintain a stable amplitude estimate? What is the minimum magnitude threshold where we can still maintain stable estimates? Can we derive average detection threshold curves?
8) Can our local coda spectra be used for high-frequency seismic discrimination, for example, coda spectral ratios?
9) Can the spectral shape of the local, coda-derived source spectra provide depth-of-burial information?

RESEARCH TO BE ACCOMPLISHED

In this project, we plan to demonstrate the capability of providing significantly lower uncertainties in yield and source estimation by extending the well-established regional narrowband coda methodology to local distances in regions of little to no calibration data using both *P* and *S*-wave codas. Furthermore, because of its stable nature, local coda-derived source spectra will be used to characterize a range of different event types (e.g., shallow and normal-depth earthquakes, mining-related explosions and their associated events, nuclear tests, rock bursts, and volcanic-related events). The motivation for using the coda comes from the fact that it has unique properties that, if exploited fully, can significantly improve our ability to monitor small events at local distances. For example, local high-frequency (>~0.5 Hz) *S*-wave coda has the unique property of homogenizing its energy over a volume of the Earth's crust such that path corrections for distances less than ~200 km are not necessary or minimal. Furthermore, the local coda averages over the focal sphere as well as the source-time function of the event, thus eliminating the need for dense seismic networks. Even in regions of strong lateral complexity, the local coda has been shown to be very stable, usually a factor of 4-to-5 times less variable than direct *S*-phases. This means that to achieve the same level of precision with the traditional direct phases, one would need a local network composed of ~16-to-25 stations surrounding the source, which in most cases would be unrealistic. Because the coda averages over the 3-D crustal heterogeneity as well as the source radiation pattern, it is ideal for small-event local monitoring with as few as one station. To demonstrate this, Figure 1 shows interstation magnitude results for Nevada Test Site (NTS) explosions recorded at near-regional distances (e.g., 200 to 300 km away). Here we compare the inter-station performance between $m_b(L_g)$, $m_b(Pn)$ and $m_b(L_g\text{coda})$ from Mayeda (1993). We observe that the coda-based m_b's have the lowest standard deviation by roughly a factor of 4 to 5. This property makes it ideal for monitoring situations where station coverage is sparse.

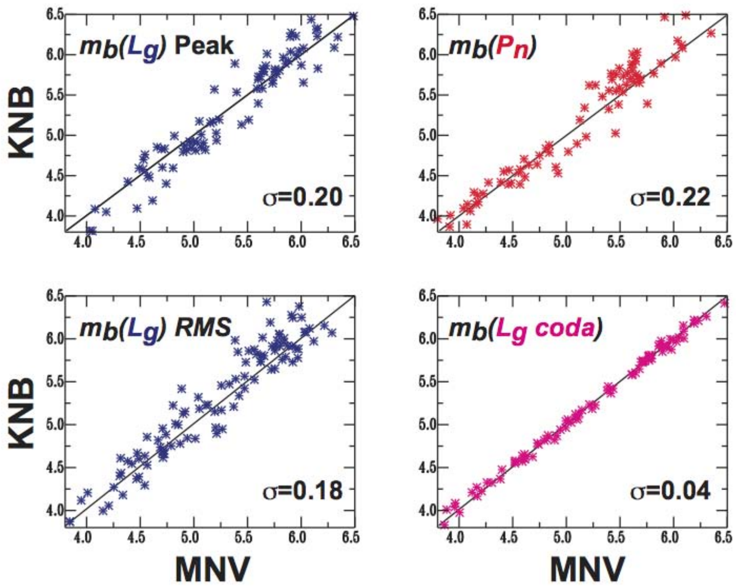

Figure 1. Interstation comparisons of magnitude at two near-regional stations, KNB (Δ ~250 km) and MNV (Δ ~200 km) (from Mayeda, 1993). Note that the scatter in the coda-derived m_b's (lower right) are a factor of 4-to-5 times smaller than the conventional regional magnitude measures using direct *P* and L_g.

For regional applications of the coda methodology, path corrections can be significant and the Department of Energy (DOE) labs have a large effort in calibrating broad regions. However, for local monitoring, path effects on the coda are not as important. For example, Figure 2 illustrates a unique property of coda waves that has been the basis of numerous studies over the past several decades, namely that the coda approaches a homogeneous distribution in space and time behind the expanding direct-wave front (e.g., Aki, 1969; Aki and Chouet, 1975; Phillips and Aki, 1986). In this example we show three panels of three events that are recorded at station BKS and another station, SAO, located ~140 km to the southeast. The three events were chosen such that one was relatively close to BKS, the other roughly in between, and the last event was close to SAO. In all panels, we see that the coda envelope levels are approximately the same, independent of the source-station distance. This is in sharp contrast to the direct waves (*P*, *S*, and L_g), which differ significantly in amplitude because of attenuation, geometrical spreading, and radiation pattern. A way to help visualize this is to imagine the direct *S*-wave moving radially away from the source. Behind the *S*-wave front, there is a pool of scattered energy in its wake that decays at the same rate, irrespective of distance from the source. As stated to the principal investigator years ago by the late Kei Aki, "It's like a kind of magic!" Whether one believes in single or multiple scattering, isotropic or nonisotropic scattering (e.g., see review by Sato and Fehler, 1998), the observational evidence clearly shows that the crust tends to homogenize the coda energy at local-to-near-regional distances (e.g., Aki, 1969). This means that *ANY* seismic station within this region would provide a stable amplitude measure irrespective of its location relative to the source origin.

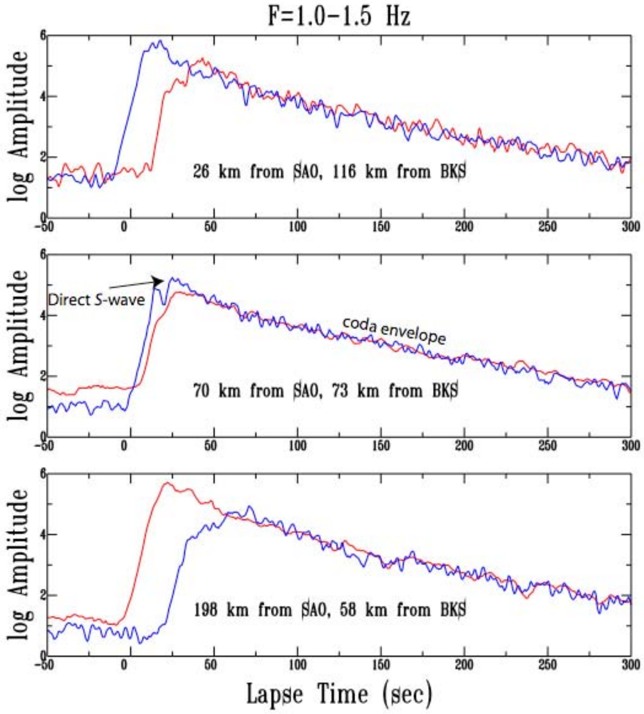

Figure 2. Example envelopes (*f*=1.0–1.5 Hz) for three local earthquakes located in the San Francisco Bay region recorded at stations SAO (blue) and BKS (red), part of the Berkeley Digital Seismic Network (BDSN). At this range of distances, the scattered *S* waves or "coda" are homogeneously distributed in the crust (from Mayeda et al., 2005).

As mentioned earlier, the motivation behind this study comes from the desire to estimate yield accurately and characterize the source, especially those that are small, or in regions of high regional attenuation. Ground-based nuclear explosion monitoring relies heavily on teleseismic and regional sensors that are sparsely distributed around the world, usually with station spacing on the order of ~1,000 km or more. Station distribution and regional attenuation will determine what size event can be reasonably recorded and processed. However, if local assets could be obtained, this would allow for much higher signal-to-noise ratio measurements. The size of the event, the emplacement conditions, and regional attenuation structure will dictate what calibration steps one would have to undertake. For example, in a highly attenuative region such as Iran, high frequency waves (f >~2 Hz) would likely be missing from regional seismograms even at M ~4. A local determination of the source spectra would provide a yield estimate and potentially depth-of-burial based on the location of the spectral peak in the coda-derived source spectrum. Likewise, if local monitoring were used in an on-site inspection, the background seismicity and duration of deployment will influence which calibration steps to follow.

Unlike yield estimates from magnitudes based on relative amplitudes from direct waves, estimating explosion yield from the coda has been developed around absolute source spectra (Figure 3).

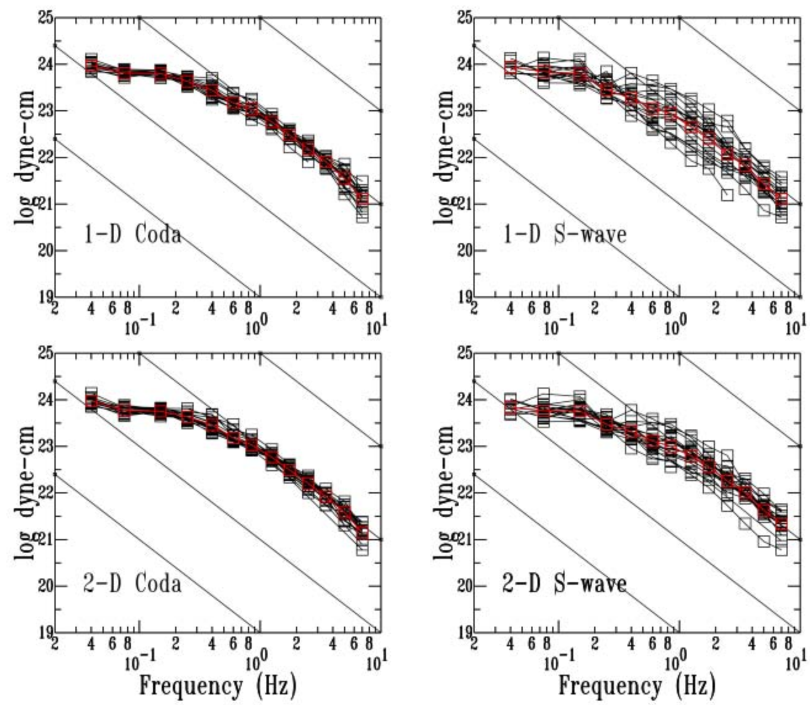

Figure 3. Absolute source spectra (moment-rate spectra) for the M_W 5.0 Napa earthquake of September 3, 2000. Top two panels show results assuming a one-dimensional (1-D), radially symmetric path corrections for coda and direct waves. Bottom panels show results using spatially varying two-dimensional (2-D) *Q*. Black lines represent individual station spectra, and red lines represent the average. Stations are situated at a variety of azimuths and range between a few tens of kilometers to over 400 km (from Mayeda et al., 2005). Notice that the coda-derived source spectra are remarkably stable in comparison with direct *S* and L_g spectra.

By using absolute spectra, we avoid potential regional biases, for example, those related to upper mantle and crustal differences (Sykes and Cifuentes, 1984). Currently, regional coda-derived amplitude-yield curves have been developed for different emplacement conditions. Local crustal structure can adversely affect the radiated energy and introduces large amplitude variability over short distances and azimuth ranges, especially at high frequency (f > ~1 Hz). In sharp contrast, the path effects on coda are negligible for local distances and in fact benefit from the crustal heterogeneity because it provides the homogenization (e.g., see Figure 2). We anticipate that local coda data from a variety of regions behave similarly, thus facilitating the construction of average local background models.

For classic yield estimation using direct waves such as teleseismic m_b, regional biases can be imprinted on the estimated yield due to low upper mantle *Q* (e.g., t* corrections for Central Asia and Novaya Zemlya). For the coda, the DOE national labs have developed a regional coda yield methodology that obviates the problem of regional bias by correcting the coda amplitudes all the way back to the absolute moment-rate spectra. The only corrections required are for the *S*-to-coda transfer function and site response, both of which are frequency dependent and could be obtained through geophysical analogy or with a single ground-truth event. To date, the coda methodology has been applied in numerous geophysically complex regions. We plan to expand upon the well-established coda methodology outlined in Mayeda et al. (2003) to test the feasibility of using well-studied, or ground-truth, regional and local-source spectra as calibration events for local stations in regions of interest. This “first of its kind” calibration procedure will be validated with data from a number of different local networks by leveraging existing data and calibration results.

The monitoring situation and region of study will dictate the calibration steps. For example, in an aseismic region, we are often faced with using geophysical analogy and transporting calibration results (e.g.,

velocity and attenuation structure) from a well-studied region to the new region of interest. The same might be true for an active region, but with no prior seismic data or calibration. On the other hand, and depending on the situation, a few or many sensors could be deployed in advance for calibration. This proposal is an initial "first-step," or scoping, study that will outline our steps to test local monitoring situations using both *P*- and *S*-wave codas. Future plans would involve characterizing a range of event types (e.g., shallow and normal-depth earthquakes, mining-related explosions and their associated events, nuclear tests, and volcanic-related events) and deriving a suite of local background models for a range of tectonic settings. For this pilot study, we will focus on active regions and test the transportability to another "active" region under the assumption of no a priori calibration data or information.

Since coda yield estimation for explosions is based upon calibration to the regional earthquake source spectrum, we will remain consistent and calibrate to earthquakes in each of our study regions. We point out that our proposed local *P*-wave coda research is not duplicative and in fact complements our ongoing regional-to-near-teleseismic *P*-coda research. One issue for the local *P*-wave coda is the short duration; however, as shown by Mayeda et al., (2003), *any* length of coda outperforms the direct arrival.

We plan to test the performance of the local background methodology, using narrowband coda envelopes in regions where calibration data may not be available from as few as one seismic sensor, perhaps clandestinely deployed within ~200 km of a monitoring region of interest. Specifically, we will compare amplitude variability between local *P* and *S* waves and their associated coda waves in a number of different regions (e.g., local data from the San Francisco Bay Area, Nevada Test Site, northern and central Italy, Yellow Sea and Korean Peninsula, Central Asia and others as needed, see Figure 4). Though most areas have ample data, we will mimic conditions where we have little-to-no ground truth and/or as few as one monitoring station. In doing so, we can compare against well-calibrated results and assess our performance.

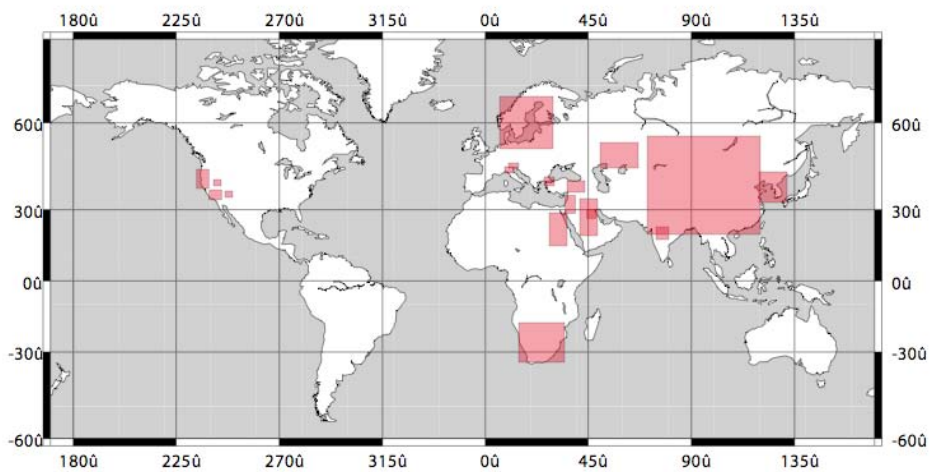

Figure 4. Map of local and near-regional coda studies for which we have preliminary coda calibrations. In addition to these waveform and calibration data, we will leverage existing in-house seismic data from Los Alamos National Laboratory (LANL) and Lawrence Livermore National Laboratory (LLNL) databases to facilitate the construction of local coda background models for various tectonic provinces.

This year we have compared coda path attenuation as a function of frequency for selected regions spanning local to near-regional distances, specifically, upstate New York (Au Sable Forks earthquake sequences and related regional events), western Iran, central Italy, San Francisco Bay area, Yellow Sea and Korean Peninsula region, and Taiwan.

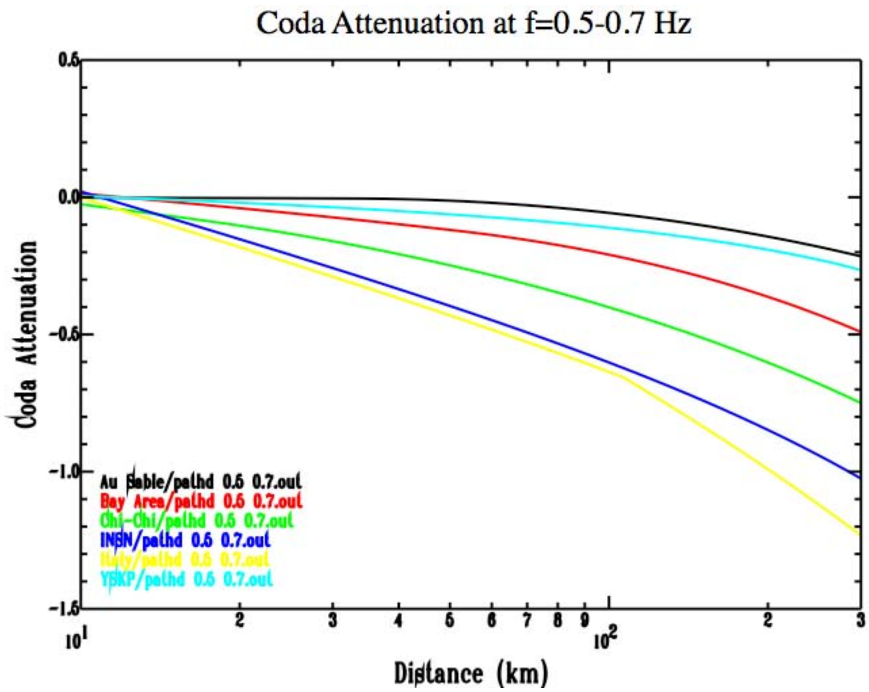

Figure 5. Coda path attenuation for the 0.5–0.7 Hz band for six different regions. In general, we find that tectonically stable regions (e.g., Korea and New York) exhibit the lowest attenuation, whereas active regions (e.g., Iran and Italy) have much steeper decay.

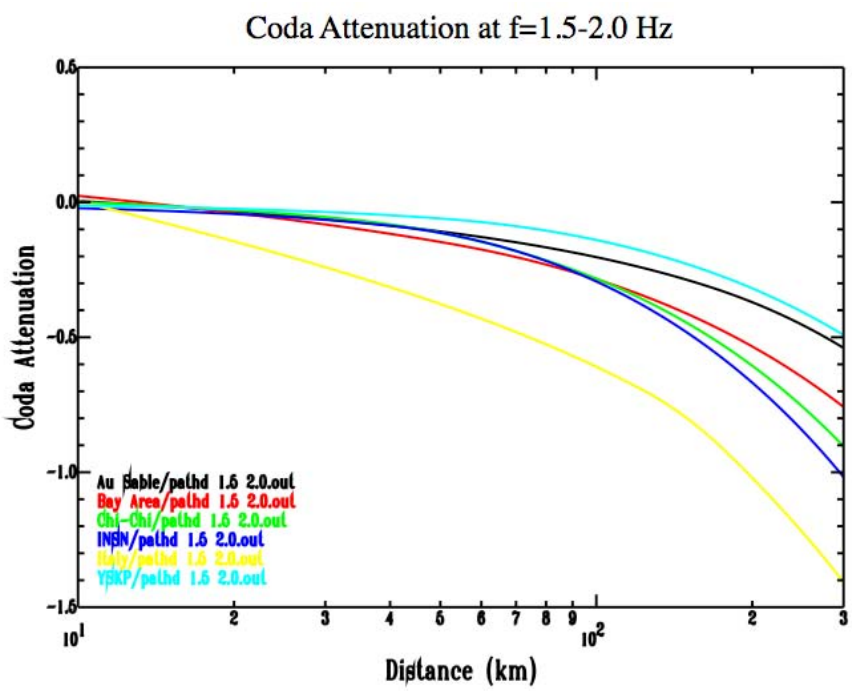

Figure 6. Coda path attenuation for the 1.5–2.0-Hz band for six different regions. In general, we find that tectonically stable regions exhibit the lowest attenuation, although we find much larger variations in contrast to the 0.5–0.7 Hz band.

In general, we can make some preliminary statements on similarities and differences between all the regions studied so far. First, we find that central Italy exhibits the strongest attenuation, followed by Taiwan and western Iran for distances ranging between ~20 and 300 km. On the other hand, upstate New York and the Korean Peninsula appear to have the lowest attenuation, which is reassuring since both regions are the most tectonically stable. The San Francisco Bay area is somewhere between the two.

CONCLUSIONS AND RECOMMENDATIONS

For this project, we have been focusing on applying the coda methodology outlined by Mayeda et al., (2003) to local data, with an emphasis on transporting local background models to similar geophysical regions. Of course if a monitoring situation provides for ample seismic data, we would opt for a complete calibration, but our first assumption will be that data may be sparse or nonexistent. At these shorter distances, we have every reason to believe that the calibration will be easier because path corrections become much less important (e.g., Figure 2). Mayeda et al., (2003) started with the following empirical equation to describe the regional coda envelope:

$$A_c(f,t,r)=W_o(f)\cdot S(f)\cdot T(f)\cdot P(r,f)\cdot H\left(t-\frac{r}{v(r,f)}\right)\cdot\left(t-\frac{r}{v(r,f)}\right)^{-\gamma(r,f)}\cdot exp\left[b(r,f)\cdot\left(t-\frac{r}{v(r,f)}\right)\right],$$

where $W_o(f)$ is the S-wave source amplitude, $S(f)$ is the site response, $T(f)$ is the S-to-coda transfer function resulting from scattering conversion, $P(r, f)$ includes the effects of geometrical spreading and attenuation (both scattering and absorption), H is the Heaviside step function, $v(r,f)$ is the peak velocity of the S-wave arrival, $\gamma(r,f)$ and $b(r,f)$ control the coda envelope shape, and t is the time in seconds from the origin time. The following figures show results of empirical results for coda path corrections, peak envelope velocity, and coda shape parameter. As stated earlier, we plan to construct average background models then test them in geophysically similar regions and assess performance.

This preliminary result shown in Figures 5 and 6 are very promising because it suggests that "local background" path corrections can be constructed, and then applied to new, local regions of monitoring interest without prior path calibration. We should point out that the coda path correction, $P(r, f)$, has been modified since the Mayeda et al., (2003) study, which adopted a functional form that looks like the Brune source spectrum (Brune, 1970) (i.e., flat at short distances, then decreasing beyond a critical distance). The new formulation (curves shown in Figures 5 and 6) is being tested by the DOE labs and appears to significantly improve local-distance data. The formulation is modified from the Street et al., (1975) equation for geometrical spreading that transitions smoothly from spherical spreading of direct S waves to cylindrical spreading for L_g waves beginning at a chosen critical distance. In the new formulation, the function is modified to allow for different spreading before the crossover distance and also provides for control on the curvature near the crossover. In addition to the background path parameters shown in Figure 5, we will derive average coda shape parameters, $b(r,f)$, and peak velocity $v(r,f)$ as a function of distance and test the extent to which average values can be applied to other geophysically similar regions. Again, we will assess the performance of the average background models by comparing directly with our ground-truth estimates, using region-specific calibrations, using the entire local dataset.

To date, we have compared coda attenuation parameters for six different regions for frequencies ranging between 0.5 and 8.0 Hz and have just completed path calibration for a seventh region, the volcanic region of Hawaii. We will continue to document other regions with which to compare and from which to draw final conclusions. We still need to look at coda shape parameters that should also be very region dependent, as evidenced by many local coda Q studies in the literature. At this point, we are on track with our proposed statement of work and are forging ahead.

We are now finished with shear wave calibration of Hawaii and will be focusing on combining the various regions and comparing their results to find correlations with the level of tectonic activity. This still leaves our local P-coda calibration study that will start in the latter part of 2008.

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